

# Frequency-Stabilization of Mode-locked Laser-based Photonic Microwave Oscillator

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**Abstract**—Photonic microwave oscillators using a mode-locked laser as the high-Q resonator have been shown to be capable of generating ultra-low phase noise microwave signals [N. Yu et al, Opt. Lett. V. 30, 1231 (2005)]. The photonic oscillator is a system that couples the optical oscillator (mode-locked laser) with the microwave oscillator (opto-electronic oscillator), which also provides the opportunity to link the stability of the two oscillators. In this paper, we will describe our recent phase-noise measurements of photonic microwave oscillators. We will also discuss our investigation of the frequency stability link between the optical and microwave frequencies in the coupled oscillator. This link is established by stabilizing the optical frequency to an atomic transition, the stability of which is transferred to the microwave signal. This system represents a unique architecture for drawing a stable microwave signal from the optical oscillator.

## I. INTRODUCTION

Actively mode-locked lasers (MLL) have been a subject of intensive study in producing high-frequency short optical pulses [1], [2], [3], [4]. The timing jitter of the pulse train is one of the critical parameters for applications such as high-speed optical sampling and optical communication [5]. The time jitter is ultimately limited by the phase noise of the microwave source that drives the mode-locked laser. Recently, it has been shown that the mode-locked laser itself can serve as a high Q microwave device. [6] This high Q results from the regenerative process of the optical modes that produce the microwave beatnote signal. We utilize this high Q resonator in an opto-electronic oscillator for generating ultra-low phase noise microwave signals. The result is the coupled opto-electronic oscillator (COEO) [7]. In this system, the microwave loop takes the electronic signal from the beatnote of the MLL. This signal is filtered, amplified and fed back into the mode locker with the proper phase. In a COEO configuration using an erbium-doped fiber amplifier (EDFA), we have demonstrated the generation of 9.2 GHz microwave signal with -150 dBc/Hz phase noise at 10 kHz offset frequency.

While the short-term phase noise of the oscillator can be improved by the use of a high Q resonator, the long-term stability often needs reference to atomic or molecular transitions. One can stabilize the microwave frequency by locking to an atomic hyperfine transition as in a conventional microwave atomic clock [8]. Here, we propose another approach to stabilize the microwave frequency through the optical frequency

stabilization. In this scheme, the optical carrier frequency is stabilized to an atomic transition. The frequency stability is transferred to the microwave in the coupled oscillator system.

In this paper, we will briefly describe the COEO experiment setup and discuss the high microwave Q in the MLL. We will present the more recent results of the system phase noise performance and limitation. Finally, we will describe a frequency stability transfer scheme in which the COEO microwave frequency is stabilized through frequency locking the optical frequency of the MLL to an atomic transition.

## II. COEO EXPERIMENT

A schematic setup of our COEO is shown in Fig. 1(a). Details of the setup can be found elsewhere [9]. It consists of two main blocks: an actively mode-locked fiber laser and an OEO loop. An OEO is a photonic microwave oscillator that converts light into stable and spectrally pure microwave signals [10]. It acquires an effective high resonator Q through the use of delay fiber, as shown in Fig. 1(b). The microwave signal is modulated onto the optical carrier from a CW laser source, recovered by the photodetector after propagating through the fiber delay line, and then fed back into the modulator with the proper gain and phase. The effective Q of the delay line makes it possible to generate the microwave signal directly with ultra-low phase noise.

In the COEO setup, however, the laser becomes part of the photonic loop. The AM modulation inside the loop forces the laser into actively mode-locked operation. The mode-locked laser has an erbium-doped fiber amplifier as the gain block. An optical bandpass filter of 1 to 3 nm is used to limit the optical gain bandwidth. Dispersion compensating fiber is also used in the loop to reduce the overall optical dispersion. The 9.2 GHz microwave bandpass filter in the feedback loop determines the microwave oscillation frequency. The rest of the microwave oscillator feedback loop consists of a rf amplifier and a phase shifter for the proper phase adjustment. The COEO generates 2 to 8 ps transform-limited optical pulses at 9.2 GHz. At the same time, it outputs the corresponding 9.2 GHz microwave signal of 25 dBm output power at the output end of the amplifier.

The origin of the high Q can be simply understood from the regenerative process of the optical modes in the MLL. In a typical fiber laser, the passive round trip gain is high,

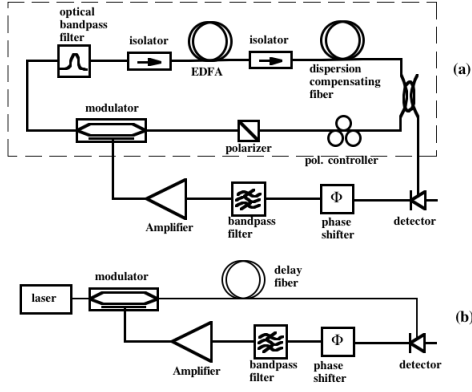


Fig. 1. (a) Schematics of the coupled opto-electronics oscillator. The dashed box is a MLL functioning as an rf filter in the OEO loop. (b) Illustration of an opto-electronic oscillator setup. The thinner lines indicate optical paths while the thicker ones the rf paths.

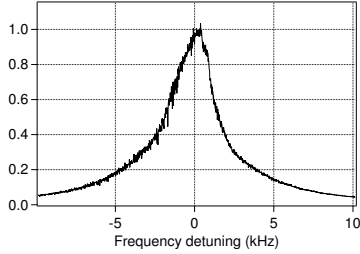


Fig. 2. The measured microwave frequency response of the laser loop. A Lorentzian fit gives 3.5 kHz FWHM.

with the finesse on the order of unit. The gain medium of the laser compensates the loss and allows long storage time of optical modes within the gain spectral range. In a near homogeneously broadening gain medium, the laser oscillates with an optical carrier, at which frequency the loop gain is clamped at unity. The loop gain falls off with the gain spectral profile of the loop. The sidebands near the carrier can be close to the threshold with little net round trip loss. Note that it is the beatnote of these sidebands that give rise to the output microwave signal. Therefore, MLL acts like a low loss and hence high  $Q$  resonator for the microwave.

The microwave frequency transfer function of the MLL can be confirmed by measuring the frequency and pulse response. Fig. 2 shows a measured frequency response of the MLL with small input signals. It was measured at 9.3 GHz with  $-40$  dBm input power at the modulator. A consistent measurement proved to be difficult due to the loop instability and the tendency of injection locking. Nevertheless, the measurement indicates a narrow bandwidth. A Lorentzian function fit gives a FWHM bandwidth of  $\delta\nu_0 = 3.5$  kHz. Note that the round trip loss of the laser loop is about  $-10$  dB. The narrow bandwidth is the consequence of the significant regenerative gain.

The impulse response can be studied with the ring-down time measurement. We applied an off-resonance phase step-function to the input and recorded the time it takes for the system to reestablish the new phase. The result is the phase

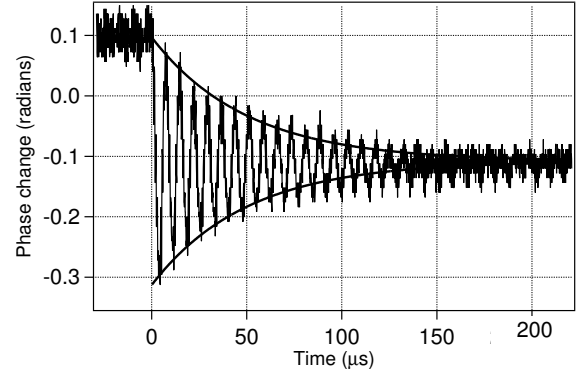


Fig. 3. Off-resonance phase ring-down time measurement. The beatnote frequency corresponds to the detuning.

ring down curve as shown in Fig. 3. The beat frequency corresponds to the frequency detuning. Fitting the envelope of the ringing curve in Fig. 3 gives the decay time of  $50$   $\mu$ s. Again, it confirms that the MLL behaves as a high  $Q$  microwave resonator.

### III. PHASE NOISE OF COEO

According to the Leeson model of oscillator phase noise [11], the single-sideband noise power spectral density  $L(f)$  of an oscillator is simply given by

$$L(f) = \left\{ 1 + \left( \frac{\nu_0}{2Qf} \right)^2 \right\} \frac{S'_\phi(f)}{2}, \quad (1)$$

where  $S'_\phi$  is the total noise spectral density of the loop. It shows that above the Leeson frequency of  $\nu_0/2Q$  the oscillator phase noise is the same as the loop phase noise. Below Leeson frequency, however, the phase noise goes up at additional  $1/f^2$  slope. The  $1/f^2$  conversion is simply due to the fact that the phase noise is converted to the frequency noise within the bandwidth of the resonator. Eq. (1) suggests that a high  $Q$  resonance is necessary to achieve an overall low phase noise in an oscillator.

There are several noise sources in the COEO system. First of all, as in any microwave oscillator system, the microwave amplifier has thermal noise, which is a white phase noise. In addition, amplifiers have flicker ( $1/f$ ) noise at low frequencies. Therefore, the flicker noise is the dominating noise at close-in frequencies. There is a corner frequency where the flicker noise and the thermal noise crosses, beyond which the thermal noise dominates. Most amplifiers used in our system have the corner frequency about 10 kHz.

For the photonic system here, there are two additional fundamental noises - shot noise at the detector and spontaneous emission noise in the laser. The combined noise is the residual noise of the MLL as a microwave device. Both noise sources are white. There is no flicker noise observed in all our measurements above the white noise similar to that in semiconductor microwave amplifiers. The noise of mode-locked lasers has been studied extensively in the literature.

Readers are referred to literature for detailed analysis and modeling [12]. It is worth pointing out that a low noise microwave source is necessary to measure the residual noise of the MLL because of its effective high Q.

The shot noise of our system at the detector is on the order of -160 dB/Hz for 2 mW of optical power, taking into account the fiber coupling and detector efficiencies. This is below the amplifier thermal noise in our system. The spontaneous emission in an active optical medium is quantum mechanical in nature. It is well established that the spectral density of spontaneous emission is one photon per second per Hz or -160 dBm/Hz for our laser at 1550 nm. This noise is regeneratively amplified the same way as the signal, which is responsible for the high Q. Therefore, within the regenerative bandwidth of the MLL (i.e. the Leeson frequency), the ASE noise is still white but increased by the regenerative gain. Outside the bandwidth, it falls as  $1/f^2$ . This is exactly the reason why a regenerative loop by a microwave amplifier will not improve the oscillator phase noise even though one can achieve higher Q. Compared with microwave amplifiers, the low ASE and flicker noises in the optical amplifier make it possible to make use of the regenerative Q for reducing the phase noise of oscillators.

In a previous report, it was shown that the oscillator noise spectrum has a  $1/f^3$  flicker phase noise at low-frequencies, and a phase noise of -140 dBc/Hz at 10 kHz and then to the -145 dBc/Hz amplifier noise floor at 100 kHz which is the upper frequency limit of our homodyne measurement technique. The oscillator phase noise has been further improved recently with the use of a lower noise power amplifier. Fig. 4 shows the measured phase noises of the COEO with two configurations. The use of 1 nm rather than 3 nm filter makes the system for stable and less critical to parameter optimization. The narrower bandwidth increases pulse width and lowers the Q. The longer 750 m loop fiber length makes up the lost Q. In the latter case, the phase noise of the oscillator reaches -150 dBc/Hz at 10 kHz offset frequency and higher. It is consistent with the amplifier noise specification, which is also plotted in the figure for reference. Note that there is no indication that the oscillator phase noise is limited by ASE or shot noises even at the noise level measured.

#### IV. FREQUENCY STABILIZATION

The ultra-low phase noise of the COEO is a result of the regeneratively enhanced microwave Q in the MLL. The close-in noise is dominated by the microwave amplifier flicker noise. At still longer time scale, the resonator frequency stability will be limited by the thermal and power fluctuations in MLL. To improve the long-term stability of the COEO, one has to lock the frequency to an atomic reference. This has been demonstrated using microwave atomic transition [8]. We are taking a new approach to stabilize the COEO microwave frequency by utilizing the coupled opto-electronic oscillator itself. By taking the advantage of high frequency stability achievable in optical frequency, in this scheme, we lock the optical frequency to an atomic optical transition. The high

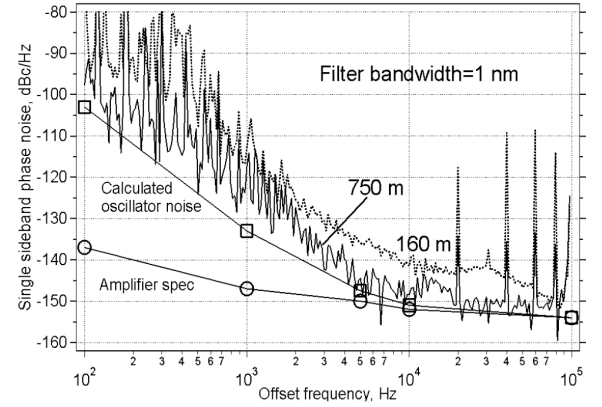


Fig. 4. Measured oscillator single-sideband phase noise plot. The single-sideband phase noise of the microwave amplifier at the same input power (-15 dBm) is also shown in the plot.

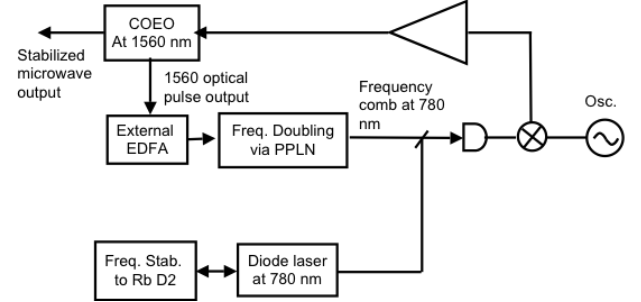


Fig. 5. The block diagram of the frequency stabilization scheme for COEO. The phase locking loop within the COEO is not shown.

optical frequency stability will be transferred to the microwave frequency in the COEO.

The mode-locked laser in the COEO generates an optical comb spaced by 10 GHz, the frequency of which is primarily determined by the MLL loop length and the microwave feedback phase. We have shown that the MLL serves as a very high Q microwave resonator. The equivalent microwave transmission linewidth is on the order of 1 kHz. With such a high Q value, the microwave feedback phase has less sensitivity to the overall oscillation frequency and can be stabilized. A micro radian feedback phase stability will allow  $10^{-14}$  fractional stability at 10 GHz. The microwave oscillation frequency will be mostly determined by the MLL free spectral mode spacing, which in turn is related to the optical frequency. The optical frequency can be stabilized by locking the frequency to an atomic transition. The loop dispersion and its fluctuation can be passively or actively stabilized if needed.

The overall experimental scheme is illustrated in Fig. 5. It consists of the COEO, which generates a comb of optical frequency at 1560 nm, a frequency doubling setup which doubles the 1560 nm to 780 nm; a cw laser at 780 nm frequency-locked to the Rb D2 transition; and an optical phase locking loop that keeps the COEO optical frequency locked to the cw laser frequency.

The optical frequency stabilization to alkaline D2 lines has been investigated before. [13]. With a simple AOM-based frequency-modulation saturation scheme, it was shown that the stability of  $10^{-13}$  at 1 sec. can be achieved with both Rb at 780 nm and Cs at 850 nm. In these demonstrations, no attempt was made to stabilize cell temperature, ambient magnetic field, or laser intensities, all of which effect the frequency stability. With some attention to the overall system stability, we believe that the stabilized COEO can reach a long-term microwave frequency stability floor in the region of  $10^{-13}$ .

## V. CONCLUSION

We have shown that an actively mode-locked laser can serve as a Q high microwave resonator in an photonic oscillator. A Q of  $3 \times 10^6$  has been demonstrated with an EDFA-based fiber laser in a coupled opto-electronics oscillator configuration. With this effective Q of the resonator, the oscillator phase noise as low as -150 dBc/Hz at 10 kHz offset frequency has been achieved in the 9.2 GHz oscillator. This phase noise is still limited by that of the microwave amplifier in the oscillator loop. We propose to stabilize the long-term frequency stability via frequency stability transfer in the COEO by referencing to an atomic optical transition.

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